NHDOT SPR2 PROGRAM
RESEARCH PROGRESS REPORT

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a progress report at least every three months during the project duration. Reports are due the 5th of the month following the end of the quarter. Please provide a project update even if no work was done during this reporting period.

<table>
<tr><td colspan="2">Project #
26962M</td><td>Report Period Year: 2018
☐ Q1 (Jan-Mar) X Q2 (Apr-Jun) ☐Q3 (Jul-Sep) ☐ Q4 (Oct-Dec)</td></tr>
<tr><td colspan="3">Project Title:
Evaluation of Gusset-less Truss Connection to Aid Bridge Inspection and Condition Assessment</td></tr>
<tr><td colspan="3">Project Investigator: Erin S. Bell Co-Project Investigator: Ricardo A. Medina
Phone: (603)862-3850 E-mail: erin.bell@unh.edu</td></tr>
<tr><td>Research Start Date:
December 15, 2016</td><td>Research End Date:
December 31, 2018</td><td>Project schedule status:
☐ On schedule ☐ Ahead of schedule X Behind schedule</td></tr>
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Brief Project Description:

The Memorial Bridge connecting Portsmouth, NH and Kittery, ME was re-opened to traffic in 2013. One of the major innovations of the reconstructed bridge is the first ever gusset-less truss connection in a vehicular bridge in the United States. Traditional gusset plates are the most vulnerable element in a truss-bridge structure and a source of significant cost, effort, and concern for bridge managers and owners. The goal of the proposed research is to integrate field-collected performance data, laboratory experimental testing, and physics-based structural modeling to develop a protocol to assess the condition and predict the remaining life of the gusset-less truss connections used at the Memorial Bridge. It is anticipated that the aforementioned approach will be modified to develop a framework to extend this protocol for application to future innovative structural elements.

The objectives of this project are to:

- Original Objective: Create two specimen pairs (A and B) of a scale model of a gusset-less connection from the Memorial Bridge. Specimen pair A (top chord connection) will be tested to failure in a quasi-static testing protocol and Specimen pair B (bottom chord connection) will be tested for fatigue performance. Modified Objective: Create two specimens that are a scaled model of the gusset-less connection from the Memorial Bridge focused on the bend radius weld section of the connection.
- Conduct quasi-static set of tests on each member of Specimen A to determine stress distribution in the connection.
- Evaluate these results in conjunction with field collected data and analytical models that are the work product of a complimentary FHWA-AID DEMO project to: (i) further understand and quantify the structural performance of the gusset-less connection, and (ii) validate analytical models.
- Conduct fatigue testing on Specimen pair B and collect performance data to determine the stress pattern and predict fatigue failure mode.
- Compare the findings of this project with the FHWA guideline for connection assessment to facilitate the development of an evaluation protocol for inspection and structural condition assessment.

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Progress this Quarter (include meetings, installations, equipment purchases, significant progress, etc.):

Complete Literature Review and Finalize Testing Plan

These tasks were completed during the last quarter of 2017 and first quarter of 2018.

Design and Construction of Scale Models

During the second quarter of 2017, weld specimens with and without defects were fabricated to evaluate the fatigue performance of intact and defective 7/16" welds (see Figure 1). As part of this effort, a mock test was performed. Due to limitations of the testing machine, significant slippage was present during the cyclic test and an alternative testing approach was designed. The Civil and Environmental Engineering Department procured grips to be attached to the Instron Universal Testing Machine at the UNH Structural Engineering Laboratory. The advantage of using the aforementioned grips is twofold: (i) the grips prevents any slippage in the response once the specimens are exposed to cyclic loading, and (ii) time and resources are saved given that specimens do not need to be machined to a circular cross-section and specimens with square cross-sections can be tested without modifications. Figure 1 shows one of the specimens to be tested. The only machining necessary involved reducing the cross-section in the middle of the specimen (where the weld is located) in order to induce fatigue failure at this location. The grips arrived toward the end of the third quarter and testing in October and November demonstrated that they were defective. Material Testing Technology (MTT) were contacted, and after a few weeks going back and forth with them, the original grips were returned, and a new set of grips were sent to us at the beginning of December. Further delays related to the testing apparatus have delayed the coupon testing to summer 2018. Fortunately, this testing can be done in parallel with testing of the small-scale specimens of the gusset-less connection.

Figure 1: Example weld specimen

Due to the focus on the fatigue testing in the small-scale connection during this quarter, the testing on the weld specimen was not performed in the second quarter of 2018 and it is planned to happen next quarter. The grips from Material Testing Technology (MTT) are still available for the test.

Analytical Models of Small-scale Physical Specimens

This task was completed in the first quarter of 2018.

Fatigue Testing

- Setup and Specimen

At the beginning of this quarter, the support components of the test setup were delivered. In addition, the two specimens were obtained from CANAM Bridges (same fabricators of the Memorial Bridge gusset-less connection). The specimens were sand blasted prior to shipping. Figure 2 shows a layout of the setup, and Figure 3 the testing apparatus with the instrumented specimen.

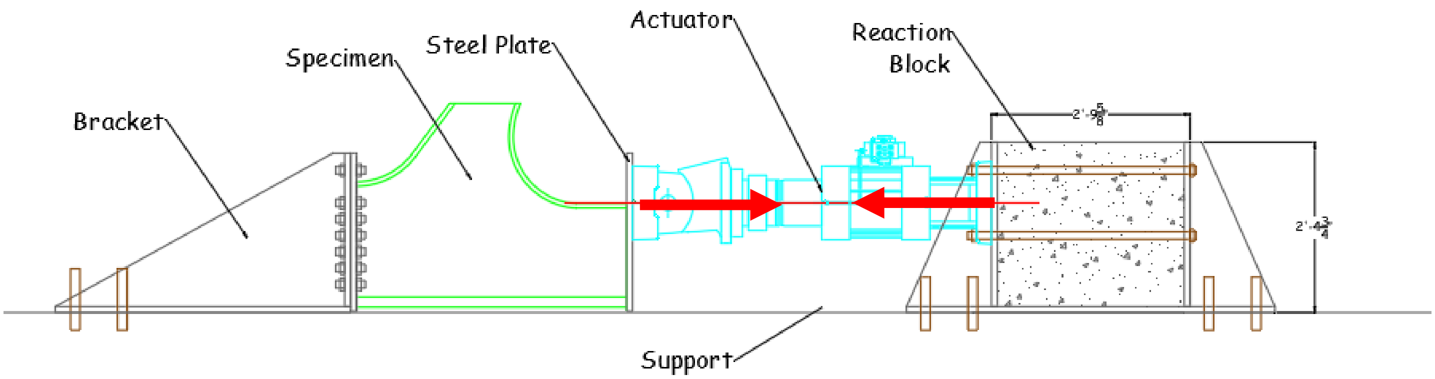


Figure 2: Schematic of setup for fatigue testing (tensile loads only)

Figure 3: Testing apparatus with instrumented specimen

- Instrumentation

During this quarter, the instrumentation plan was defined and the material ordered. The first decision was to use the same strain rosettes specifications used in the instrumentation of the Memorial Bridge. From a rosette, strain is collected from all directions, allowing the calculation of principal strains in the location where it is bonded and then apply equations to convert to principal stresses. It is important to have the principal stresses at the area under the curvature to compare with the maximum principal stresses provided by HNTB Corporation in their Summary Design Calculation for the critical load combination related to the fatigue limit state. This strain rosette is spot welded to the surface, and the company that sells it, Hitec Products, provided instructions and training for the graduate students for the proper installation of the rosettes. In addition, uniaxial strain gauges were installed at the specimen close to the supports to verify boundaries conditions. Figure 4 shows the locations of the strain rosettes and uniaxial gauges on both sides of the specimen.

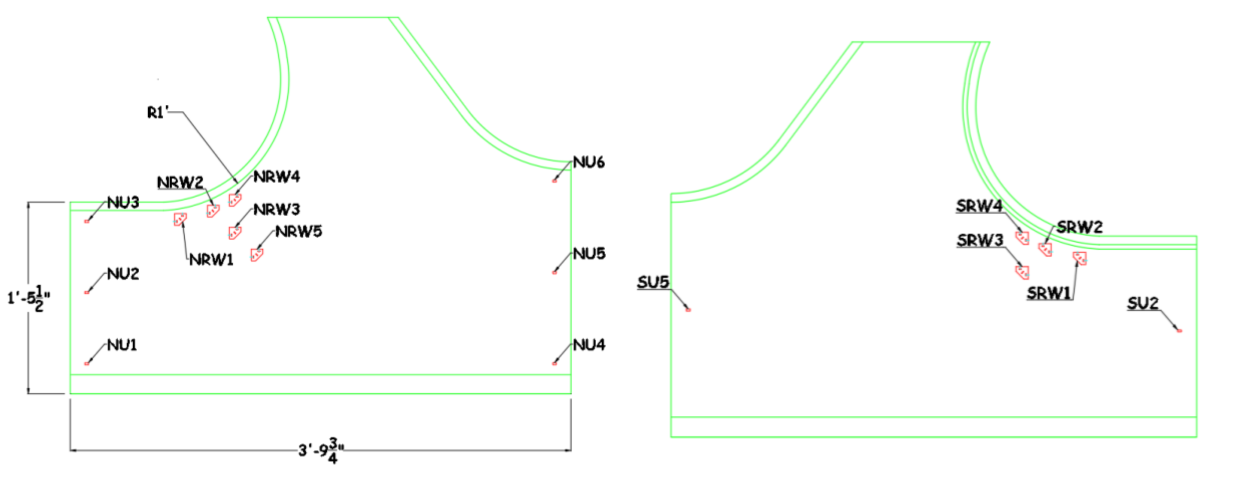


Figure 4: Gauges instrumentation (a) north side, (b) south side of the specimen

As part of the instrumentation, LVDTs are placed at the plates located at each end of the specimen (Figure 5) as well as at the end of both supports. The LVTDs at the plates are held by clamps which use a steel stand to adjust their height. Having the LVTDs at those specified locations provides information on the potential translation and rotation of the plates, and the potential translation of the overall setup. This information is important for data analysis and model verification.

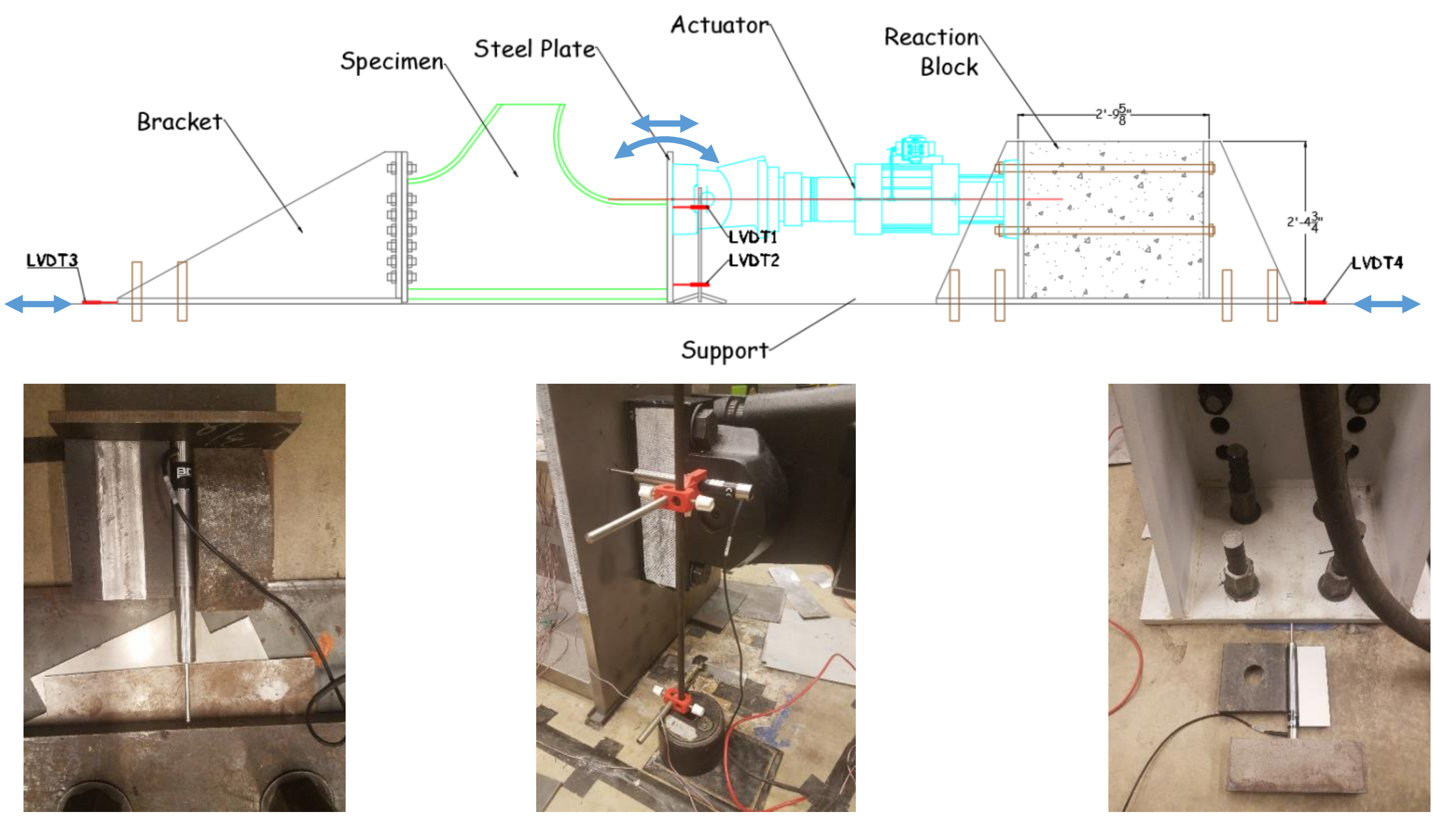


Figure 5: Illustration of LVDTs locations

For the gauges installation, the surface was prepared by sanding the surface until a smooth and clean surface was achieved, and then cleaning it with appropriate chemicals following the approach recommended by the manufacturers of the gauges.

- DIC instrumentation

In addition to the strain gauges shown in Figure 5, Digital Image Correlation (DIC) is utilized as a non-contact measurement method. DIC is a measurement method that identifies groups of pixels, called subsets, and tracks the movement of those subsets across multiple images. The tracking is calculating the displacement vectors of the subsets and using them to calculate displacement and strain with relation to a reference image. This method can be used for both two- and three-dimensional measurements of the strains and displacements of the surface of the specimen. The advantage of DIC as a measurement tool is that it provides measurements across the entire surface that are captured by the cameras as opposed to strain gauges, which are limited to discrete points on the specimen. Additionally, the surface preparation needed for DIC is not significant compared to that of strain gauges.

In this test, both two- and three-dimensional DIC will be used. The two-dimensional DIC was used to capture strains and displacements in the web of the connection during an initial static-loading test. Figure 6 shows a picture of the instrumentation for the initial test. The goal of this initial test was to use two-dimensional DIC to identify the strain contours of the specimen given the applied load, which should reasonably match the strain contours provided by the analysis conducted by HNTB Corporation, as well as the strain contours from the finite element model (FEM) of the connection developed at UNH. Figure 7 presents an image of the Abaqus model developed and used at UNH. These measurements were compared to those obtained from the strain gauges in NUI1, NUI2 and NUI3 (Figure 5) to verify that the measurements were accurate and finalize the locations at which the strain rosettes were placed for the fatigue test.

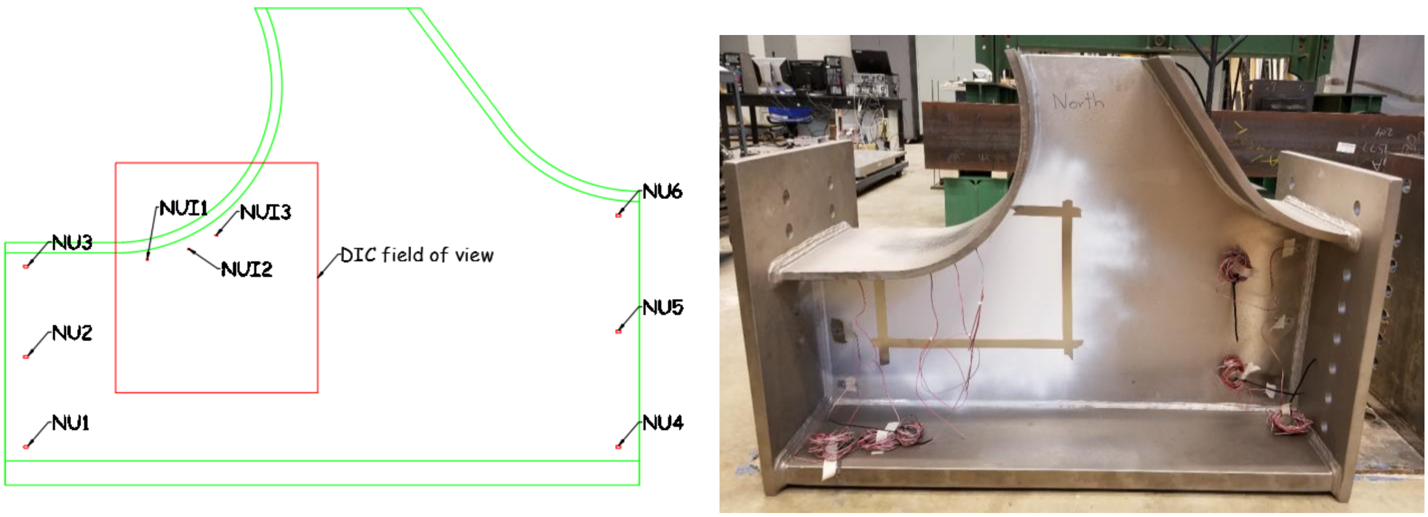


Figure 6: Instrumentation for initial test

The three-dimensional DIC is used for the full-scale fatigue test to capture the area-of-interest. The area-of-interest is focused on the interaction between the web and the underside of the top flange. Due to geometric constraints, and not wanting to damage the weld with surface preparation, strain gauges cannot be placed on or particularly close to the weld. Using three-dimensional DIC in this area will characterize the behavior, through displacement and strain measurements, of the web and flange as well as the weld.

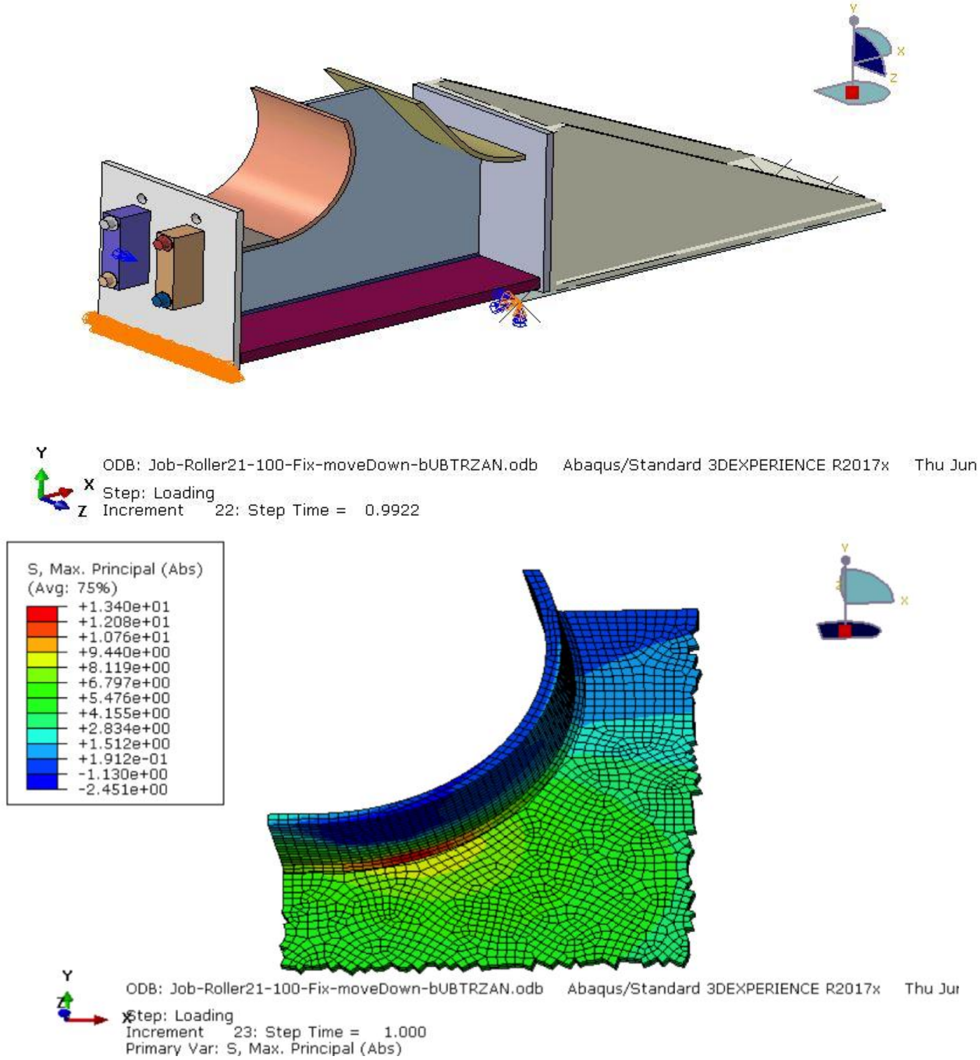


Figure 7: Abaqus model developed at UNH

- Test specifications

As discussed in previous reports, the fatigue test consist of cyclic force-controlled tests, beginning at the design load stress, followed by the allowable stress from the fatigue category of the weld and then increased until failure happens and/or the capacity of the actuator is reached. The frequency of the test is 3.5 Hz only in tension. Figure 8 is an example fatigue load protocol for 2 seconds of test that was used to calibrate the actuator. The 105 kips load shown in the figure is close to the load capacity of the actuator (which is rated at 110 kips) and it is considered the maximum loading condition to be applied to the specimen if fatigue failure has not occurred during previous force levels.

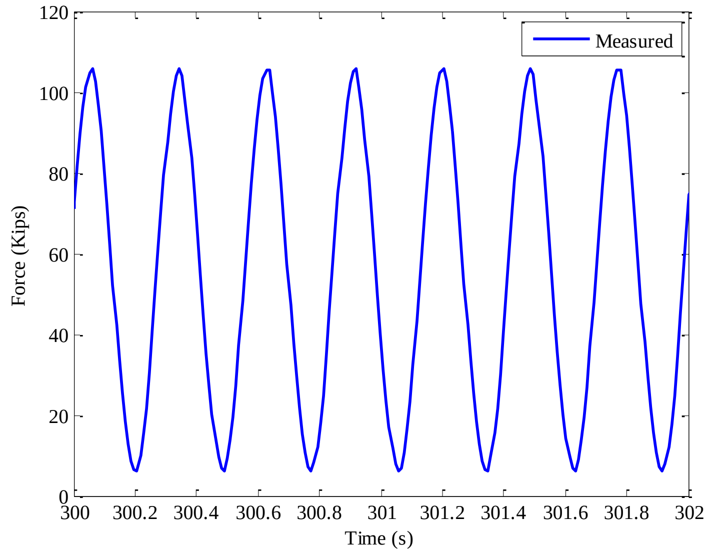


Figure 8: Fatigue load protocol example

Unfortunately, the test was not completed this quarter due to a delay in the calibration of the actuator. Initially, the calibration of the actuator would be done at UNH as soon as the reaction block was available. When MTS (actuator's brand) did their visit prior to the installation, it was concluded that the actuator needed to return to the company for calibration. The actuator returned from calibration in April 4th, and the visit for installation took place later in the month of April. The test of the first specimen is currently underway.

- Coupon Test

For material characterization, coupon specimens were fabricated at UNH Machine Shop from the same batch used to fabricate the web and the flanges of the specimens. These tests will be conducted under tensile load at the Instron Machine. The plates for the tensile test were provided by CANAM Bridges.

- Residual stress

To better characterize the stress state of the connection, residual stress tests have been performed. The residual stress tests have been performed prior to testing and are being performed during testing using a blind-hole analysis. This means that the specimen is fitted with a specialized strain rosette and a small-diameter hole is incrementally drilled into the specimen to a specified depth (see Figure 9). This drilling relieves the stresses around the hole, which results in strains measured by the strain rosette. These strains can be mathematically related to the total stresses that were present in the specimen before drilling. Due to the unique fabrication of this specimen, it is deemed important to quantify the residual stresses due to the cold-bending process, and the residual stresses around the weld area. In order to have a reasonable benchmark, a residual stress test was also performed on a plate of the same material that did not undergo any bending or fabrication. Sample results using the aforementioned approach are shown in Figure 10. This figure depicts the estimated strains along the depth of the top flange.

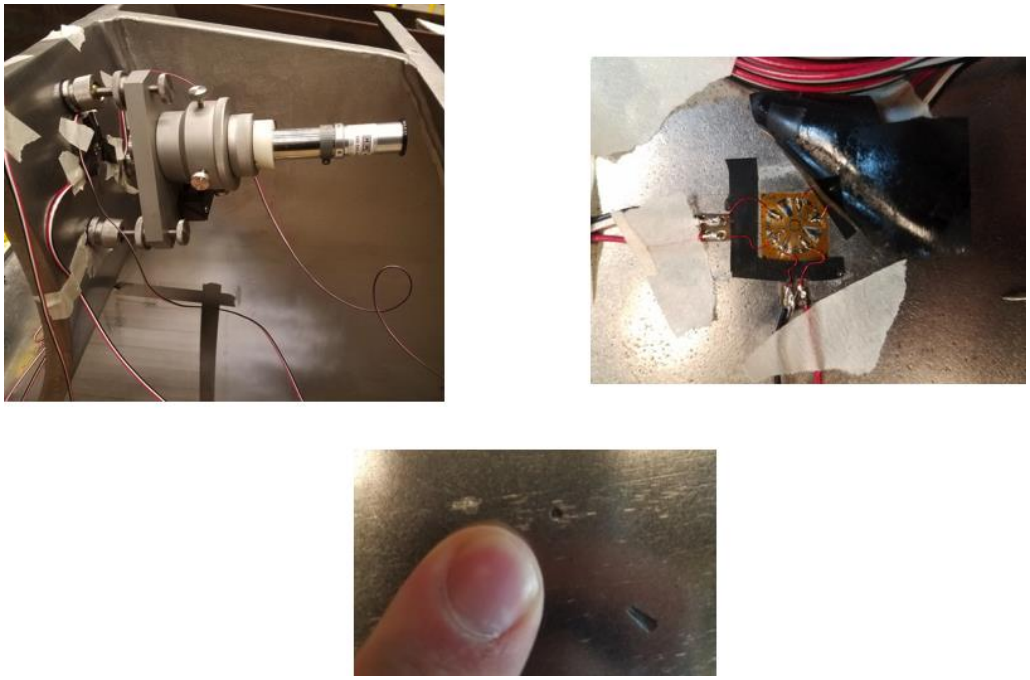


Figure 9: Residual stress test (a) drill rig, (b) strain rosette, (c) 1/8" diameter hole.

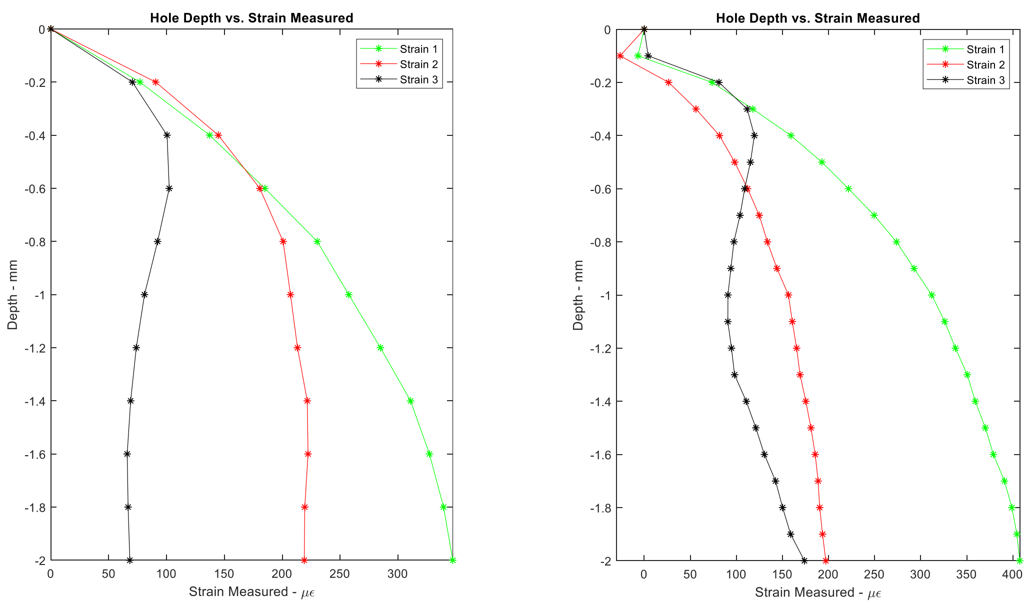
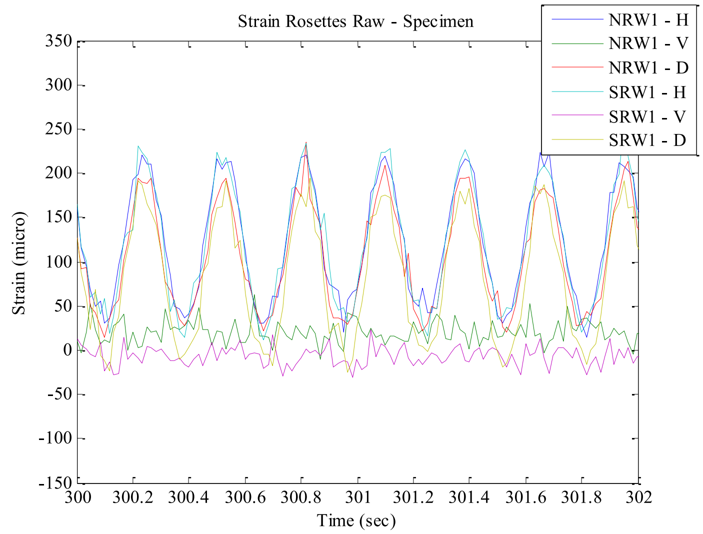


Figure 10: Sample results from residual stress tests of top flange (a) inside curve and (b) outside curve

Data Analysis and Interpretation of Laboratory Testing

Sample data form preliminary tests is presented in Figure 11, Figure 12, Figure 13 and Figure 14 below. Note the reasonable agreement between the measured strain ranges and those predicted by the finite element model.

Direction	Max Strain Range (με)	Model Strain Range (με)	Model Stress (ksi)
Vertical	20	50	2.2
Horizontal	215	266	6.5
Diagonal	190	-	-
Max. Principal	-	287	7.2



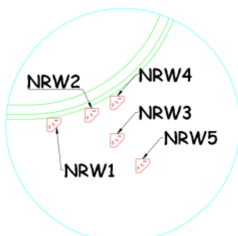
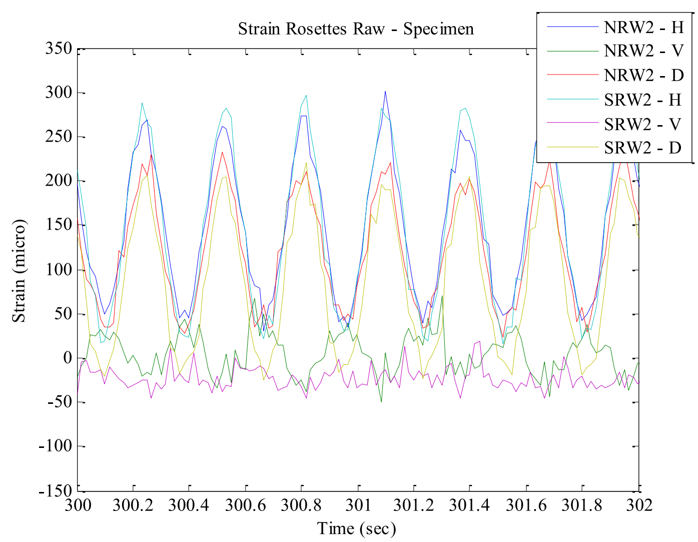


Figure 11: Preliminary testing – Strain close to weld region of interest (rosettes at position 1)

Direction	Max Strain Range (με)	Model Strain Range (με)	Model Stress (ksi)
Vertical	50	8.8	0.8
Horizontal	230	196	8.1
Diagonal	200	-	-
Max. Principal	-	225	8.6



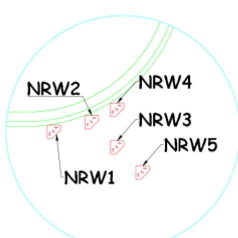
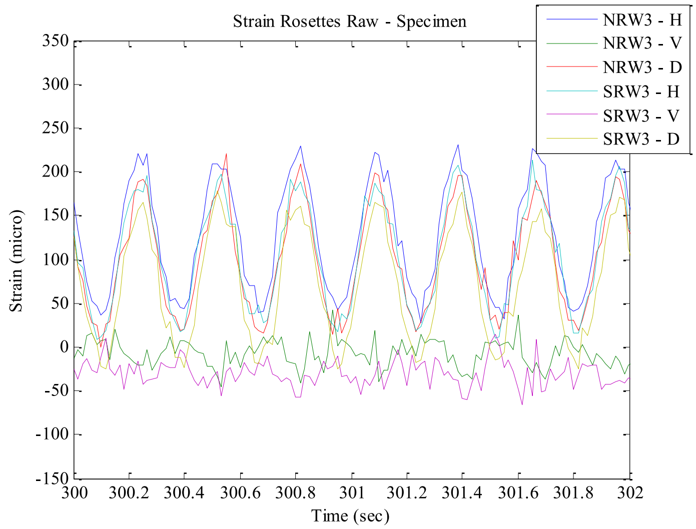


Figure 12: Preliminary testing – Strain close to weld region of interest (rosettes at position 2)

Direction	Max Strain Range (με)	Model Strain Range (με)	Model Stress (ksi)
Vertical	50	88	0.3
Horizontal	200	266	7.8
Diagonal	180	-	-
Max. Principal	-	273	8.0



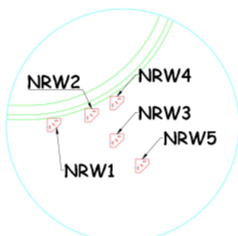
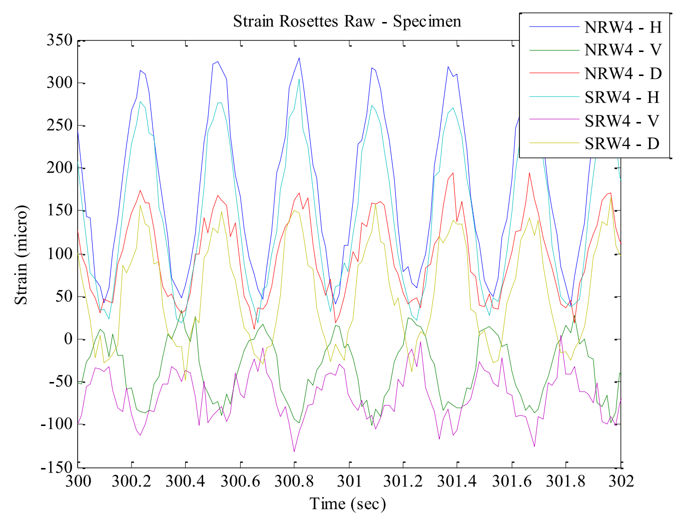


Figure 13: Preliminary testing – Strain close to weld region of interest (rosettes at position 3)

Direction	Max Strain Range (με)	Model Strain Range (με)	Model Stress (ksi)
Vertical	80	47	0.27
Horizontal	278	194	5.84
Diagonal	156	-	-
Max. Principal	-	225	6.6



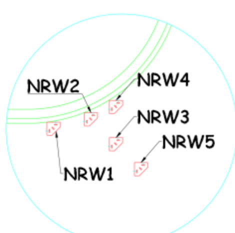


Figure 14: Preliminary testing – Strain close to weld region of interest (rosettes at position 4)

Moreover, Table 1 shows a detailed description of the progress during this report period, including multiple challenges that the research team faced and had to resolve.

Table 1. Description of activities performed from April – June 2018 – Progress and challenges

Month	Test Performed	Summary
April	Initial Instrumentation	Installed uniaxial strain gauges and DIC speckle pattern on the specimen.
	Actuator Tuning - Monotonic	Tuning the force-controlled load application of the actuator.
	Initial Monotonic Testing	A 12-kip, tensile load, was applied to the specimen to study the strain distribution compared the expected strain distribution from the numerical model.
	Initial System Identification	Instrumented all components of the test setup to identify displacements and rotations at key points to characterize the system. The specimen was loaded, in tension, monotonically at three different load levels; 12, 25, and 50 kips. During the testing, a significant vertical displacement was measured at the tip of the specimen.
May	Initial System Identification - Cont.	Some modifications for the anchors were made to prevent the specimen tip from reaching the ground. Once this was accomplished the specimen was monotonically loaded with 90kips in tension. A residual movement was noted, and attributed to gaps between the anchors and the plates of the supports.
	Residual Stresses - Specimen	Began planning measurement locations for residual stress drilling. Once the locations were identified, two holes were drilled on the top flange using the blind-hole drilling method. These holes were chosen to isolate the effect of the cold-bending process.
	System Troubleshooting	To remove the source of the residual movements, the specimen was loaded to 90 kips, in tension, and held at 90 kips for approximately one hour. During this test it was noted that the rate of movement slowed significantly compared to the previous tests.

	Actuator Tuning - Cyclic	Tuning force-controlled load application with a cyclic ramp load. Initial tuning was performed with a loading frequency of 0.5Hz, and a maximum and minimum tensile load of 70 and 30 kips respectively. During the testing a buzzing sound was noted from the support under the actuator. It was also noted that the reaction frame was displacing and rotating significantly.
	System Modifications	Based on the tuning, the vertical movement of the specimen was applying a lateral load on the actuator. It was decided to remove the support under the actuator and to support the tip of the specimen to prevent any damage to the actuator. Additionally, it was decided to pour concrete in the reaction frame to add stiffness to the system.
June	DIC - Troubleshooting	While the concrete was curing, some additional testing was done in terms of measurements. With the equipment that was available, the DIC setup was optimized to reduce as much noise in the data as feasible.
	Residual Stress - Cont.	Initial stress calculations were performed using multiple numerical methods. Additional holes were drilled in a flat piece of material that matches the properties of the flange on the specimen. This measurement will be used as a baseline to isolate the effects of the fabrication on the specimen.
	Actuator tuning	Once the concrete was cured, the actuator was tuned at multiple loads and frequencies. The final tuning was performed at a frequency of 3.5hz and a max. and min. load of 105 and 5 kips, respectively. It was noted that the anchors of the supports were visually moving during the tuning.

	System ID	Using DIC and LVDTs, the system was characterized in terms of displacements and rotations at key locations. Based on this, shims were added where there may have been rocking of the supports or specimen due to uneven surfaces in the specimens, due to manufacturing and the floor. Additionally, at the location of the attachment between the actuator and specimen, some high local strains were observed. To reduce these strains, the actuator was lowered in relation to the specimen.
	Started Cyclic Testing	Initially, 5000 cycles were applied, as a sine wave, using the previously mentioned tuning parameters. The data was evaluated and some modifications to the supports were made. These modifications included additional shimming of the specimen and supports. An additional 5000 cycles were applied, and the data was evaluated.
July	System Troubleshooting	The motion of the supports noted during the cyclic testing was significant, therefore, it was decided to increase the torque on the anchor bolts to create a better contact area. This significantly reduced the motion in the supports and increased the overall stiffness of the system
	Testing Protocol development	A testing protocol and checklist was developed to ensure consistency across the entire testing period. Testing increments, thresholds for stopping the testing, and data acquisition rates were determined.
	Cyclic Testing - Cont.	A 2-hour fatigue test was run, totaling 25,200 cycles using the previously mentioned loading protocol.
	Residual Stress - Cont.	It was decided to incrementally measure the total stress, including the residual, on the specimen. This will indicate if there has been a redistribution of stress in the specimen.

Evaluation Protocol for Inspection and Condition Assessment
There was no progress on this task during this reporting period.

Final Report and Presentation
There was no progress on this task during this reporting period.

Meetings
A TAG meeting was held at UNH in Durham on June 21 2018 to update the NHDOT on the research activities and solicit

their input on the remaining research tasks. Dr. Bell (PI), Dr. Medina (co-PI), Duncan McGeehan (graduate student), Shokoufeh Zargar (graduate student) and Andrew Lanza (undergraduate student) participated in this meeting from UNH.

Dr. Medina, Dr. Bell, Duncan McGeehan and Shokoufeh Zargar and Maryam Mashayekhizadeh (graduate student) had a conference call with Ted Zoli at the HNTB offices to discuss various aspects of this project, especially some of the details related to future fatigue testing activities that could be part of future projects depending on the results of this research effort in April 2018.

Items needed from NHDOT (i.e., Concurrence, Sub-contract, Assignments, Samples, Testing, etc):

There are no items needed from the NHDOT at this time.

The research team would like to request a TAG meeting for August to review test results. This meeting could be live or virtual using Zoom®.

Anticipated research next 3 months:

Complete the fatigue testing of weld samples with the new grips on the universal testing machine at the structural high bay.

Complete strength testing of the small-scale physical specimens of the gusset-less Memorial Bridge connection to verify the structural models.

Conduct fatigue testing of the small-scale physical specimens of the gusset-less Memorial Bridge connection.

Circumstances affecting project: Describe any challenges encountered or anticipated that might affect the completion of the project within the time, scope, and budget, along with recommended solutions to those problems.

As described in the previous quarterly reports, delays associated with specimen fabrication, the need to modify the Instron Universal Testing Machine at UNH, the receipt of defective grips for fatigue testing of weld specimens, technical issues relating to the data acquisition system at the Memorial Bridge have negatively affected the schedule of this project.

Tasks (from Work Plan)	Planned % Complete	Actual % Complete
Evaluation of Gusset-less Truss Connection to Aid Bridge Inspection and Condition Assessment		
Literature Review and Finalize Testing Plan	**100**	**100**
Design and Construction of Small-scale Models	**100**	**100**
Quasi-Static Testing to Failure – Replaced by Load Test of the in-service connection at the Memorial Bridge	**100**	**100**
Validation of Structural Connection Analytical Model	**100**	**100**
Fatigue Testing	**75**	**20**
Data Analysis and Interpretation of Laboratory Testing	**50**	**20**
Evaluation Protocol for Inspection and Condition Assessment	**0**	**0**
Final Report and Poster	**0**	**0**